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Design and Implementation of a Universal Integrated Wi-Fi Controller for Smart Buildings

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Abstract: Internet of things (IoT) technologies deal with the control over communication networks for different applications of different fields, such as residential buildings, commercial buildings, agricultural farms, transport vehicles, and manufacturing industries. Wi-Fi is a family of protocols for wireless local area networks, based on the IEEE 802.11 standards. Recently, a microcontroller with a built-in Wi-Fi module can be considered one of the most recent technologies of IoT. Nevertheless, most of the available research on Wi-Fi controllers is dedicated to a specific application. This paper aims to design and implement a universal hardware platform for a Wi-Fi controller that can be integrated with multiple applications for residential and commercial buildings. The proposed system is based on Ep8266 NodeMCU with a built-in WiFi module. Input modules and output modules of the proposed system are designed to be suited for various voltage levels. The proposed system was implemented and evaluated for multiple applications. The first application deals with controlling residential building loads with an embedded web server on the Wi-Fi controller and web browser on smartphones. The second one is related to integration with the remote access control application of commercial buildings, which is based on Radio Frequency Identification (RFID) cards with Wiegand protocol and based on User Datagram Protocol (UDP) with Internet Protocol (IP).

Keywords: *Wi-Fi Controller, Internet of Things (IoT), Universal Integration, Smart Buildings.*

1. INTRODUCTION

The Internet of Things (IoT) technology has spread in recent years because of the expansion and related cost reduction of Internet networks, microcontrollers, and associated open-source technologies. The Internet of Things can be classified according to its technologies as listed in the survey conducted on [1] that concerns just one application. Nevertheless, it can be organized into two main research domains, which are networking protocols and control applications.

The research in the control domain aims at developing systems for a specific application; such as agricultural and irrigation as in references [2-4], smart-home control in general, specified items of smart-home control as in [5-9], smart home security as in [10-12], as well as measuring and monitoring of power and energy of the household as in [13-17].

Most of the proposed designs of these researches share the same concepts of interfacing the controller with the sensors and actuators for one application under study. On the other hand, the objective of this research is to design and implement a universal Wi-Fi controller that can be universally integrated with multiple applications rather than one.

The research in networking protocols concern the development of communication network protocols, and cloud servers, with fewer concerns about control applications [18-21]. Nevertheless, these researches have a considerable effort to develop a prototype model of the Wi-Fi controller for validation and testing.

Although this research domain is out of the scope of this paper, developing a universal integrated hardware platform for Wi-Fi controllers will reduce that mentioned unnecessarily wasted engineering effort and cost for developing a prototype model of a Wi-Fi controller. In summary, achieving the objectives of this research of reducing engineering efforts, time as well as cost, requires designing a controller that can be universally integrated with multiple building applications rather than one, which in return requires integration of multiple universal interfacing modules and the main controller on the same PCB.

2. Design and Implementation of the Proposed Universal Wi-Fi controller

2.1 Design

The proposed system of the universal Wi-Fi controller is designed according to the performance specifications that are stated in [24-25] and **Table 1**.

Table 1. The requirements for various input and output units of the proposed system.

System units	time response (ms)	Voltage range (V)
Controller	<=50	-
Digital input	<=0.020	3.3-24
Digital output	<=100	3.3-24
Analog input	<=50	3.3-10

These performance specifications are determined according to the optimal requirements of the target buildings applications that compromise between efficiency and cost. The buildings are considered slow dynamic processes such as temperature control of Heating, Ventilation and Air Conditioning systems (HVAC) or standalone cooling packages, turning on or off electrical load, and access control systems. So, there is no need for a high speed response system with high cost. For example, the insulated environment of buildings has large time constants for their temperature control on the order of minutes of about 1-5 minutes. If we assume that, the time constant in the worst case is about 1 second, as in the case of free air space, the sampling rate and control algorithms have to be 10 to 20 times faster than the controlled process, which implies that the controller and its analog inputs have to support 20 Hz or 50 ms processing speed as a minimum. A wide input voltage range of analog input, from 3.3V to 10V, can support a wide dynamic range of temperature sensors for example.

For the digital input unit of the system, the highest speed requirements that can be faced are for serial data interfacing with sensors, such as the Wiegand protocol, which is used with an RFID card reader, with time response of about 20 us. The voltage of digital input sensors can be 3.3V, 5V, 12V, and 24V; so it is necessary to support this wide dynamic range with the same digital input. For digital output units, the interfacing is usually for turning on or off or tripping the electrical loads, which requires a time response less than or equal to 100ms, as for automatic circuit breakers. The voltage of digital output interfacing can be 3.3V or 5V to interface with other controllers; or 5V, 12V, or 24V to interface with external actuators such as DC relays, TRIAC, or SCR; which can be used to actuate larger loads or actuators such as contactors, motors, etc.

Consequently, the system is designed according to the block diagram of **Figure 1** below. The system is based on the ESP8266 controller with a built-in Wi-Fi module.

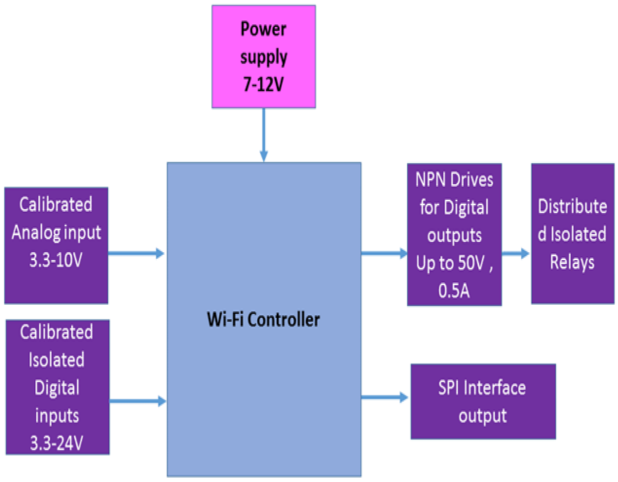


Fig .1. Block diagram of the proposed system.

Figure 2 below shows the schematic design of the system with its main controller, digital input, digital output, analog input, and distributed relay modules, whereas **Fig 3** shows the PCB design of the system for the central unit and the distributed relay boards.

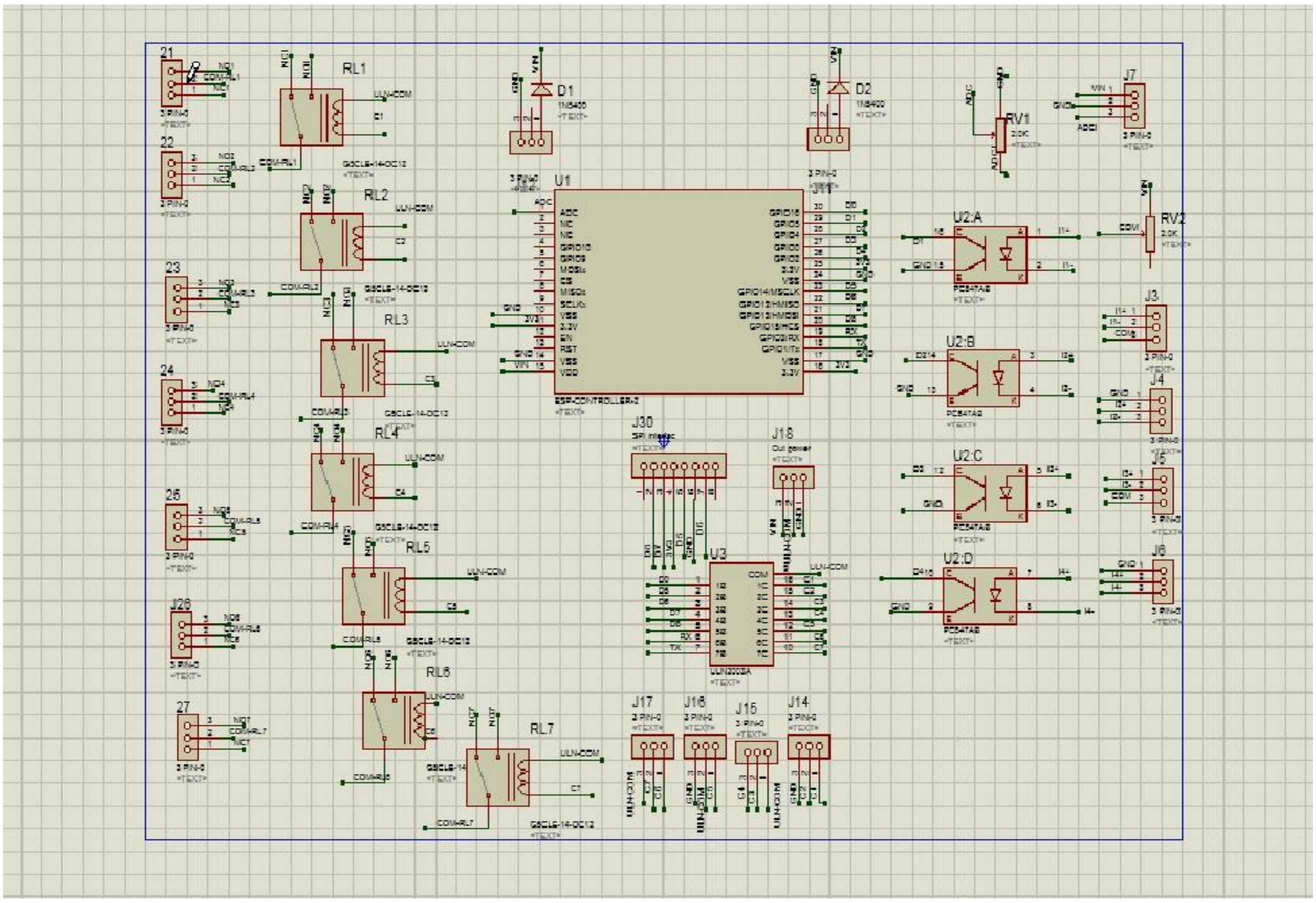


Fig .2. The Schematic design of the system.

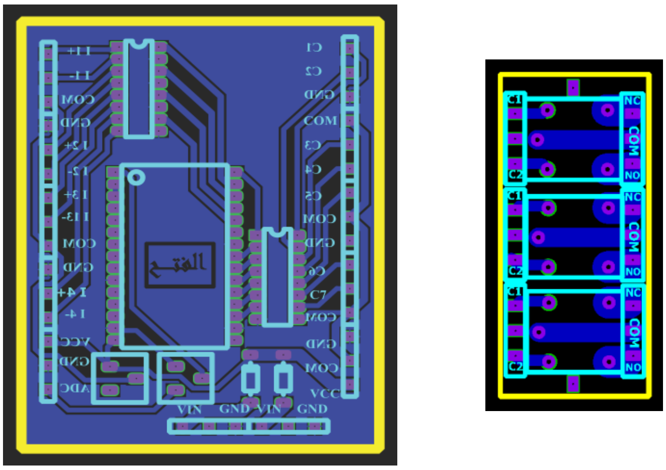


Fig .3. (Left) The PCB design of the system for the central unit board. (Right) The distributed relay boards

The design includes four digitally isolated inputs with optocouplers that can be calibrated for a wide input voltage range (3.3-24V); as well as different types for binary sensors such as NPN-transistor output type, PNP transistor output type, or normal switches. In addition to that, the controller has an analog input, which can be calibrated for a wide input voltage range (3.3-10V).

Moreover, the controller supports dual 7-12V power supplies, where one is used as a backup battery source. Furthermore, it contains seven digital outputs with a relay drive with up to 50V and 0.5A, which is isolated from loads with distributed relays. In addition, a serial peripheral interface (SPI) socket is used to interface with other sensors or modules that support it. To achieve the versatility of supported applications, the relay drive is maintained on the same board as the main controller; whereas, the relays are distributed on the field on different boards.

2.2 Implementation

The design was implemented as a hardware prototype, which is demonstrated in **Figure 4** below.

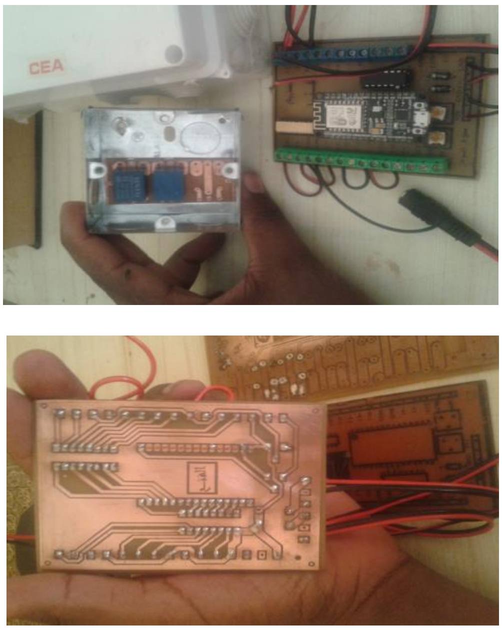


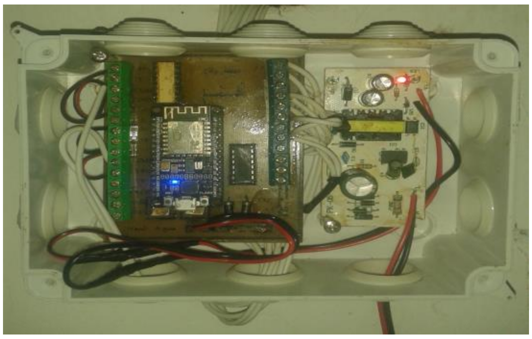
Fig .4. (Top) The implementation of the main controller board and distributed board. (Bottom) The bottom view of the main controller board.

3. Results and Discussion

In this section, the system has been evaluated for integration with multiple applications. The first one deals with the control of residential building loads using a web browser on smartphones locally. In the second application, the system has been integrated with access control for security gates of commercial buildings, which is based on Radio Frequency Identification (RFID) cards with Wiegand protocol.

3.1 Integration with Smart Home Applications

On the hardware level, the main Wi-Fi controller board is combined with a 12V power supply, as shown in **Figure 5--a**, and is interfaced through digital inputs with a water level sensor of an evaporative cooler. In addition, the main Wi-Fi controller is interfaced through distributed output relays with lamps, a traditional fan, and an evaporative cooler. The distributed boards are installed on the same available box of manual switches, as shown in **Figure 5-b**. The wiring for inputs and outputs interfacing is accomplished through the existing trunks.



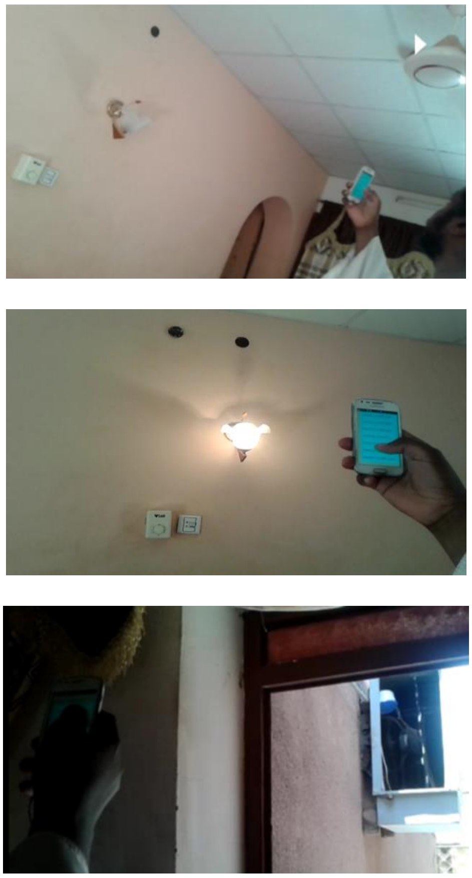
(a)

(b)

Fig .5. (a) The main Wi-Fi controller board is combined with a 12V power supply (b) The distributed relays board is installed on the same box of manual switch.

On the software level, the Wi-Fi controller is programmed as an embedded HTTP web severer with Transmission Control Protocol/Internet Protocol (TCP/IP) and embedded Hypertext Markup Language (HTML)/JavaScript page. This page is transmitted upon request to the web browser of a smart mobile phone or Personal computer and it contains regularly updated information about inputs and outputs with JavaScripts shown in **Figure 6-a**.

(a)



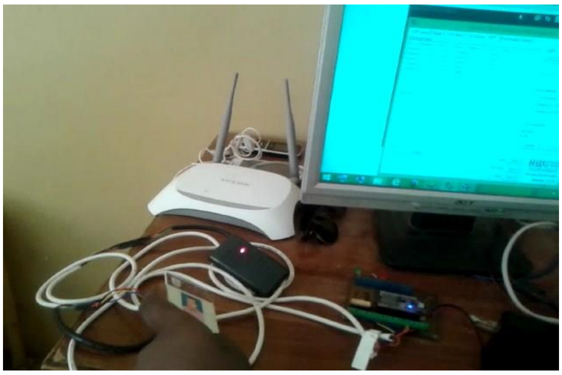
(b)

Fig .6. (a) HTML/JavaScript page as requested with a smartphone web browser. (b) Example of controlling different residential building loads such as a lamp (top), fan (middle), and evaporative cooler (bottom) with a smartphone webpage as an example.

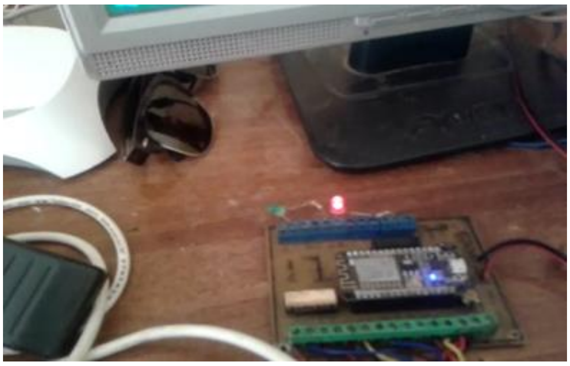
Any interfaced load can be switched on or off with the buttons on the web page, and any input can be monitored with the related field on the web page. For example, **Figure 6-b** demonstrates the controlling of different loads with a smartphone webpage. Besides; conditional events are programmed with IF statements, such as turning on/off the pump of the evaporative cooler according to the water level digital input. For more information, a video demonstration can be found on [22].

3.2 Integration with Access Control Applications of Smart Buildings

Although the application of the previous section is considered a real field implementation, in this section the universal integration of the Wi-Fi controller is evaluated with a prototype model to prove the concepts. On the hardware level, the Wi-Fi controller is interfaced with two RFID reader modules. The RFID modules are hardwired with the main controller with serial Wiegand protocol through its digital inputs as shown in **Figure 7-a**; and the embedded Wi-Fi module on the main controller is used as a communication link with the access control server, without using any other communication modules like XBee. Likewise, the Wi-Fi controller is interfaced with LEDs through its digital outputs drive to emulate the gate door actuators as shown in **Figure 7-b**.



(a)



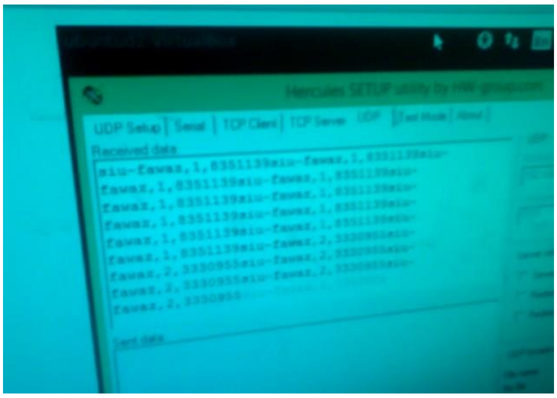
(b)

Fig .7. (a) the Wi-Fi controller is interfaced with RFID readers with serial Wiegand protocol through its digital inputs. (b) The Wi-Fi controller is interfaced with LEDs through its digital output drives to emulate the gate door actuators.

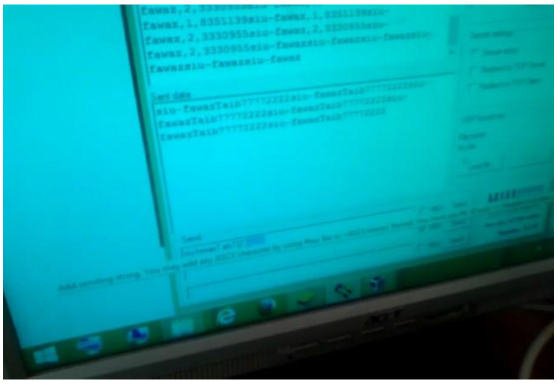
On the software level, the Hercules Ethernet Converter SETUP utility is used to emulate the access control server with User Datagram Protocol (UDP) protocol. On the other hand, the Wi-Fi controller is programmed to decode precisely with interrupt service routine the data comes from the Wiegand RFID card reader, when the card is moved around it as shown previously in **Figure 7-a**. In that case, these decoded data; which are Wiegand protocol type, number of the card, and number of the reader and the related gate; are sent with User Datagram Protocol (UDP) protocol to the access control server as shown in **Figure 8-a**.

Upon reception of the decoded information at the access control server, it can send an opening encoded command for an authorized person to the Wi-Fi controller as shown in **Figure 8-b**. After that, the Wi-Fi controller decodes these commands to ensure it is sent from an authorized server with authorized command, therefore It will actuate the gate through its digital output as shown previously in **Figure 7-b**. For more information, a video demonstration can be found on [23].

Later, the Wi-Fi controller system was successfully integrated with a real-field access gate for integration evaluation purposes, where the Wi-Fi controller output drive unit was connected with the digital input to the local control unit for that gate.



(a)



(b)

Fig .8. (a) The authorized RFID card data are sent from the Wi-Fi controller to the access control server with UDP protocol. (b) the authorized opening command is sent from the access control server to the WiFi controller with UDP protocol.

3.3 Discussion

This first version of the proposed universal controller series has been released in 2017, as recorded in [22] and [23], to be the first mature and ready-to-use system worldwide for reducing engineering efforts and time as the main contribution. This requires the design of a controller that can be universally integrated with multiple building applications, rather than one which in return requires the integration of multiple universal interfacing modules and the main controller on the same PCB.

The ability of the Wi-Fi controller to universally integrate with multiple applications originates from the nature of the input and output interfacing units and mechanisms of the design.

For example, the design of small distributed relay boards, to be embedded directly into the existing boxes of load switches, enables the load switches and their distributed relay boards to be interfaced by using small cross-section control wires with the digital output module of the controller. This, in turn, reduces the cost of using large cross-section power cables for load switches and reduces the effort and time for deploying these large cables through the existing cable trunks.

Moreover, the embedded Wi-Fi module on the controller can reduce the serial wiring cost of RS-485 and Ethernet of the traditional Direct Digital Controller (DDC) of the building management systems with building, automation, and control networks (BACnet) protocol

Also, the presence of calibrated input units enables the interfacing with digital sensors even if they are far away and face high voltage drops because of the resistance of the connecting wire. In addition, the possibility of using drives of output units without relays enables integration with applications that require less current but higher speed. Furthermore, the use of a low-cost Wi-Fi built-in unit enables integration with program applications of smartphones, computers, servers, and cloud systems with various communication protocols.

Although this paper is focused mainly on the design and implementation of the proposed system, the comprehensive integration and performance evaluation of the system have been discussed in [24-25]. For input to output (End to end) control path without relays, the total minimum time response is about 0.018 ms and with relays is about 10ms, For the Wi-Fi radio channel, the round-trip time delay (RTD) in milliseconds (ms) for indoor environments is evaluated to be 30.87ms before losing the connection retransmission with 99%. These time responses meet the optimal performance specifications requirements as stated previously in the design section.

4. Conclusion

In summary, the results of successful integration with multiple smart building applications prove the concepts of universal integration of the designed Wi-Fi controller. Although the proposed design is implemented and evaluated for a limited number of applications, the principle can be generalized and used for other applications.

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